Connecting Agriculture to the Internet of Things through Sensor Networks

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Abstract—The Internet of Things (IOT), the idea of getting real-world objects connected with each other, will change the ways we organize, obtain and consume information radically. Through sensor networks, agriculture can be connected to the IOT, which allows us to create connections among agronomists, farmers and crops regardless of their geographical differences. With the help of the connections, the agronomists will have better understanding of crop growth models and farming practices will be improved as well. This paper reports on the design of the sensor network when connecting agriculture to the IOT. Reliability, management, interoperability, low cost and commercialization are considered in the design. Finally, we share our experiences in both development and deployment.

Keywords—sensor networks; Internet of Things; design; agriculture

I. INTRODUCTION

The idea of getting real-world objects connected with each other shapes the concept of the Internet of Things (IOT) that will radically transform corporate, community, and personal spheres [1]. As an important constituent part of the IOT, sensor networks provide us with a new instrument to observe and interact with the physical world that was unobtainable before. Connecting real world to the IOT with sensor networks promises us unusual ways to obtain, organize and consume information, and the opportunity to develop unique applications in a variety of sectors such as environment, agriculture, transportation to name a few.

A number of works have been done in the last few years on applications of sensor networks in agriculture. Burrell etc. adopted ethnographic methods to design and implement a sensor network assisting cultivation and production in a vineyard [2], which shows promising potential application of sensor networks in agriculture. By carrying out a pilot sensor network deployment in precision agriculture Langendoen etc. gave several lessons in terms of engineering and development process to computer scientists [3]. The scientists from CSIRO investigated application of sensor networks on farm and discussed the possible transformation of agriculture brought by sensor networks [4]. Meanwhile, to improve Chinese agricultural productivity, in recent years, scientists in China begin exploring applications of sensor networks in agriculture [5], [6].

Although there were many endeavors to employ information and communication technologies (ICT) to improve agriculture productivity in China before, high cost and inadequate infrastructures made it difficult to spread out these technologies. In contrast, the increasing popularity of Internet (31.8% penetration rate1) and mobile communication (60.5% penetration rate2) in China, the low cost production of embedded hardware (chips, PCB), and extensive availability of mature and reliable open-source software offer Chinese agriculture a great opportunity to make a leap by taking advantage of sensor networks. In cooperation with Northwest A&F University, we are aiming to leverage sensor networks and the current ICT to improve the production of western high value-added predominant agricultural products (e.g. apple, kiwi, melon, tomato and salvia miltiorrhiza). The aim is twofold: (1) To help agronomists have better understanding of plant growth models by equipping them with a new instrument for their observations. Through sensor networks and the Internet, the agronomists can efficiently collect abundant live data not only from their own test fields but from various farmland and greenhouses across the country, which helps them to breed or improve specific crop varieties or lines with desirable properties for specific areas. (2) To help farmers carry out farming practices more efficiently by setting up links among agronomists, farmers and crops. Limited resources, declined land conditions, recent climatic variability and inappropriate farming practices are the main reasons for the low agricultural productivity of China. With the help of Internet, mobile communication and sensor networks, the agronomists, regardless of geographical constraints, can provide timely cultivating guidance like pest management, disease and disastrous climate warnings for the farmers all around the country. The remainder of this paper is organized as follows. Section II details the trade-off in design and implementation of our system, including design goals, system architecture, hardware and software of the system. Section III describes the deployment and experiences. Finally, we provide our conclusions and present directions for future work in section IV.

II. DESIGN AND IMPLEMENTATION

Sensor networks bridge the gap between cyberspace and the real world, and thus their design is the key to connecting agriculture to the IOT. The following requirements are

1http://www.cnnic.net.cn/
2http://www.miit.gov.cn/
considered to be important during the design of sensor networks for agricultural applications:

- Reliability and longevity. Sensor networks must work reliably in the targeted environments and operate for a long period without the need of battery replacement.
- Management. Sensor networks must be remotely manageable so that the actions like diagnosis, reconfiguration, and software upgrade can be performed easily.
- Interoperability. To enable future integration, a design that allows pervasive access of sensor networks is required.
- Low cost and commercialization. The design must be affordable for Chinese users and easy for future commercialization.

In the following sections, we continue with an overview of the system architecture, and then we detail the design of hardware and software respectively.

A. System Architecture

Fig. 1 depicts the architecture of the system. In a targeted environment (greenhouses or farmland), deployed sensor nodes and relay nodes form a multi-hop network rooted at a gateway. According to tasks assigned by the gateway, the sensor nodes periodically wake up to take relevant environmental measurements and send the data directly or through multiple hops to the gateway. The measurements include temperature and relative humidity of air, temperature and moisture of soil, ambient light and CO$_2$ concentration (only for green houses). According to a gateway access protocol, the gateway repackages and sends the collected sensor data to the communication server, which stores the data into the database. The decision support system (DSS), containing various agricultural models, analyzes the database and publishes relevant guidance, like irrigation, pest management and disastrous climate warnings, to farmers via SMS. Moreover, irrigation system and greenhouse control cabinets that connect to the sensor nodes and the relay nodes can be controlled by DSS through the communication server. A web server provides an interface to view real-time data, query and run reports on historical data, create alerts and perform simple management of sensor networks. Finally, agronomists can download the sensor data from the database and refine the agricultural models in DSS.

As the above introduction has shown, connecting agriculture to the IoT involves many parts. Due to space constraint we focus on the challenge part – the design of sensor networks in this paper, rather than detail those fundamental and well-understood services.

B. Hardware

1) Sensor Nodes: Although there are sensor network products and even a complete solution\(^3\) for agriculture in the market, we decided to develop a customized sensor node out of three reasons: (1) The prices of the existing products are much higher than we could afford for our deployment. (2) Compared with integrating various agricultural sensors into the existing products, customized hardware will allow us to optimize the design to meet special requirement of the project. (3) The experiences from academia and our previous research prove the feasibility and flexibility of building sensor network system on top of customized hardware and open-source software, which will allow us to leverage the maximum results from open-source communities.

Wireless communication radio and microcontroller unit constitute the core of a sensor node. Among platforms supported by open-source communities, MSP430 + CC2420 and ATmega1281 + AT86RF230 are the two most popular combinations. Table I summarizes the features of the two platforms. For MCU, the table shows that the active current of MSP430 is nearly half of that of the ATmega1281. On the other hand, for radio module, AT86RF230 offers better receive sensitivity and higher transmit power, which makes the link budget of AT86RF230 around 9 dB higher than the CC2420. Although the MSP430 platform has competitive advantage in low-power MCU, we adopted the ATmega1281 platform for two reasons: (1) Considering the cost factor and the relatively good homogeneity of parameters to be measured, we plan sparse deployment of sensor nodes. The high link budget of AT86RF230 offers longer range communication (LOS range $\geq 200$m), and therefore allows the sparse deployment of nodes. (2) Since the microcontroller does not dominate the system power budget, the low-power

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\(^3\)eKo http://www.memsic.com/
MCU will not have a large impact on lifetime. Besides the MCU and the radio module, each sensor node is equipped with an AT45DB041 NOR flash that offers 4 Mbit of non-volatile storage for logging and upgrading software over the air.

Sensors were selected according to the specification given by agronomists. Digital sensors are preferred to analog ones because the digital ones are usually self-calibrated and easy to interface with (e.g. sensor reading, power mode selection). Moreover, each sensor node can have two optional relays for controlling various equipments like irrigation, warming and ventilation. We use NIMH battery (4.8V 2700mA) as power source for sensor nodes. An add-on solar power module can be used to support long term operation of sensor nodes when high current drain sensors are connected to the nodes. To guarantee the reliability of sensor nodes in the targeted environment, we designed special casings to provide protection for nodes as well as to allow quick replacement of broken sensors on site. Sensors with enclosure are either fitted to the casings or led out through cables. Fig. 2 shows a sensor node with a solar panel deployed in farmland and a disassembled node with various sensors.

2) Gateways: A gateway, which is a typical embedded system based on Motorola MCF5307 processor, acts as an intermediary between the sensor network and the Internet. Each gateway is connected to a sensor node through a UART port for communication with the sensor network. It also has a GPRS module for the Internet connection. Since the gateway is powered from the mains, it has a 12-hour backup power supply in case of electricity cutoff.

<table>
<thead>
<tr>
<th>Platforms</th>
<th>MSP430F1611 (CC2420)</th>
<th>ATMega1281 (AT86RF230)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCU</td>
<td>48</td>
<td>128</td>
</tr>
<tr>
<td>RAM (KB)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Active, 3V 1MHz (mA)</td>
<td>0.50</td>
<td>0.90</td>
</tr>
<tr>
<td>Sleep (µA)</td>
<td>2.60</td>
<td>1.00</td>
</tr>
<tr>
<td>Radio</td>
<td>RxSens (dBm)</td>
<td>-95</td>
</tr>
<tr>
<td></td>
<td>TxPwr (dBm)</td>
<td>-101</td>
</tr>
<tr>
<td></td>
<td>Rx (mA)</td>
<td>18.80</td>
</tr>
<tr>
<td></td>
<td>Tx (mA)</td>
<td>17.40</td>
</tr>
<tr>
<td></td>
<td>Sleep (µA)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>802.15.4 (y/n)</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table I: COMPARISON OF TWO POPULAR SENSOR NETWORK PLATFORMS.

C. Software

There are some operating systems for sensor networks such as TinyOS4, Contiki5, MantisOS6, LiteOS7 etc. We chose TinyOS as software platform for sensor nodes. TinyOS is considered to be the most prominent and active open-source community of sensor networks. Both industrial and academic members make their contribution to the community, which allows us to leverage the latest results from the community. Moreover, the main TinyOS tree is licensed under a New BSD license that makes future industrialization and commercialization easier.

All sensor nodes run software written in NesC for TinyOS 2.x. Besides platform specific parts (i.e. sensor drivers and hardware specific configuration derived from the IRIS mote), the software includes the following components: (1) Low power listening MAC. For the medium access control layer we used the default asynchronous low power listening radio stack of TinyOS 2.x. (2) Collection Tree Protocol (CTP). CTP, a core protocol in TinyOS library, is a well-tested and reliable data collection protocol specialized for environmental monitoring applications. (3) Dissemination protocol. The dissemination service, another core protocol in TinyOS library, is used by management service to reliably disseminate data through the network. (4) Management Service. Built on top of CTP and the dissemination protocol, the service provides interfaces for scheduling sensing tasks (i.e. sample interval adjustment), node state retrieval (e.g. battery voltage, next hop, neighbors), system configuration (e.g. channel configuration, watchdog reset timer). Deluge [7] is also integrated with the management service for upgrading sensor node software over the air.

Since sensor networks usually employ proprietary protocols and communicate with outside through gateways, we believe that a common access interface on the gateways is crucial for the further integration of services on the IOT. All the gateways are assumed to be capable of TCP/IP communication on top of which we designed an application protocol for the common access to the sensor networks of agricultural applications. The protocol includes simple access authentication, sensor data retrieval (synchronous and asynchronous modes) and simple management of the sensor networks. Our backend system (DSS, database and web server) is integrated with the sensor networks through the communication server that implements the protocol.

III. DEPLOYMENT AND EXPERIENCE

From February 2009 to the end of 2010, our sensor nodes have been deployed in over 10 sites including greenhouses and farmland across the Shaanxi Province in China. Over

4http://www.tinyos.net/
5http://www.sics.se/contiki/
6http://mantisos.org/
7http://www.liteos.net/
six hundred megabytes of data have been collected totally. Besides the benefit that the project brought to agronomists and farmers, the most valuable outcomes for us who build systems were experiences about building sensor networks when connecting agriculture to the IOT.

Regarding hardware design, cost and power consumption of sensor networks are determined not only by MCU and radio frequency chip but by the sensors that you can find meeting requirement of measuring certain physical properties. For example, in the project, each CO₂ concentration sensor reading consumes around 27J energy that is around 1/1344 of the total energy of the battery. We had therefore to develop the add-on solar power module to guarantee long-term operation of the sensor nodes, which was not in the plan before the CO₂ concentration sensor was selected. In the real world, incorporating your sensors into the design is the key to the success of sensor network applications.

In terms of software development, the practice of leveraging the existing works from the open-source community saved us from reinventing the wheels and allowed us to only focus on the application-specific parts including around 1400 lines of code for platform-specific parts and 2500 lines of code for the application. There is, however, cost for that. In TinyOS, we have to work with the event-based programming paradigm in which code is error prone and difficult to debug. Moreover, since there is no guarantee of correctness for open-source software, we have to dive into the code or wait for fixes from the community when there is something wrong. In practice, we kept our own branch of TinyOS and merged relevant and important changes from the community trunk code into the branch.

Deployed sensor networks are notoriously prone to failures and hard to debug even though we were using the cutting edge hardware (customized IRIS) and the upgraded de facto standard software (TinyOS 2.x), and learned lessons from veterans [3]. We approached the problem in three ways: (1) A test suite is carried out for every node before deployment to guarantee the hardware correctness. (2) We ran the application in parallel with the deployed networks on a dedicated outdoor testbed with around 10 nodes for continuous testing, which helped us to find bugs and improve the reliability of the application. (3) As a last resort, the watchdog was used to reboot nodes when there was no message traffic within certain period.

IV. CONCLUSIONS AND FUTURE WORK

As an important constituent part of the IOT, sensor networks provide us with a new instrument to observe and interact with the physical world that was unobtainable before. This paper reports on the sensor network design that enables connecting agriculture to the IOT. The connection sets up links among agronomists, farms, and crops regardless of their geographical differences, and thus improves the production of agricultural products. To meet the requirement in terms of reliability, cost and application-specific features, we designed the customized sensor node and developed the application for agriculture on top of TinyOS 2.x. A common access interface of the sensor networks for agricultural applications was created to enable further integration of the sensor networks on the IOT. The design rationale is explained in detail in the paper. Finally, we have shared our experiences about building sensor networks when connecting agriculture to the IOT.

In future work, we are planning to redesign the application on top of 6LoWPAN architecture [8], which we believe will improve the interoperability and programmability of sensor networks when connecting to the IOT. In regard to agriculture, we plan to add low-resolution cameras and employ ethnographic methods [2] to explore the possible productivity brought by ICT.

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